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Research Article

Calibration of Passive UHF RFID Tags Using Neural Networks to Measure Soil Moisture

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This paper presents a system to monitor soil moisture using standard UHF RFID tags buried on the soil. An autonomous mobile robot is also presented, which is capable to navigate on the field and automatically read the sensors, even if they are completely buried on the soil. Thus, passive RFID tags are buried on the soil, allowing wireless moisture measurement without the need of batteries for long periods. The system dispenses external cables and antennas and may be composed of a single RFID tag buried on the soil or by several RFID tags buried at different depths on the soil. An antenna coupled to a RFID reader can be pointed to the place of installation of these tags, and by measuring the received signal strength indicator (RSSI) and other parameters, it allows to estimate the amount of water on the soil. The estimation of volumetric water content (VWC) on the soil was successfully obtained and calibrated with $R^2 > 0.9$ using neural networks trained with experimental data from a reference capacitive soil moisture sensor. In addition to the simplified installation procedure, the system allows manual or automatic reading through irrigation systems or other systems to control irrigation systems. The system has been evaluated in several experiments, and nine tags were buried on the field, being used for at least three years. Experimental results show that it is possible to read tags at 40 cm deep in the soil with the RFID reader antenna 10 cm far from the soil surface.

1. Introduction

Recent years have shown significant growth in the development and use of information and communication technologies in agricultural applications. One well-known example is precision agriculture, which makes it possible to produce accurate maps and apply fertilizers and chemical products to the soil or to the plants with centimeter level precision. However, to work properly, these technologies require field measurements and reliable data, which could be provided by sensors scattered on the field.

One important parameter to be measured is soil moisture, as irrigation is one of the most important factors in plant development. In fact, up to 80% of all the world potable water is used for agriculture [1], which indicates that the adequate use of the water is important to avoid impacts on the environment and optimize the use of water supply. To implement irrigation systems, some approaches rely simply on letting the water continuously flow, others use timers, and other practices rely on the irrigation scheduling based on the reading of soil moisture sensors, which can save a considerable amount of water, up to 88% when compared to irrigation systems based on timers [2].

When sensor-based irrigation is used, certain types of sensors must be selected. In most cases, these sensors need cables or batteries, which require constant maintenance to keep the system working. Based on these requirements, Robinson et al. [3] and Ruiz-Garcia et al. [4] claim that there are several challenges for precision agriculture and suggested the need of new sensor designs that should provide devices

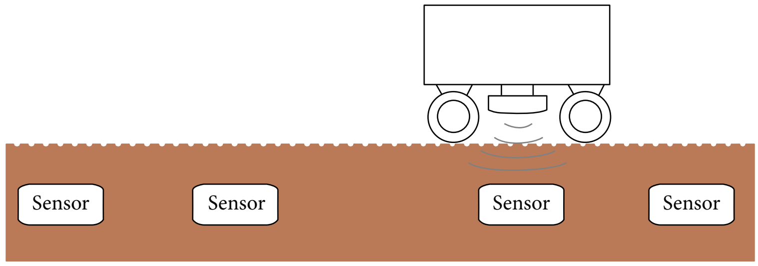


Figure 1: Overview of the proposed architecture. A robot, or other devices, can wirelessly read batteryless, buried sensors.

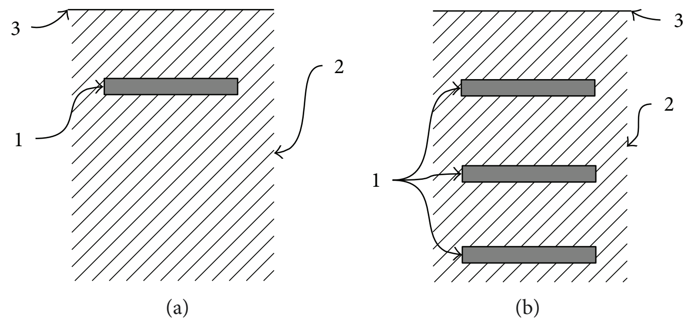


Figure 2: Conceptual design of the proposed system. Batteryless and wireless RFID-based sensors (1) can be buried under the soil surface (3), on the soil (2) at one depth (a), or at several different depths (b).

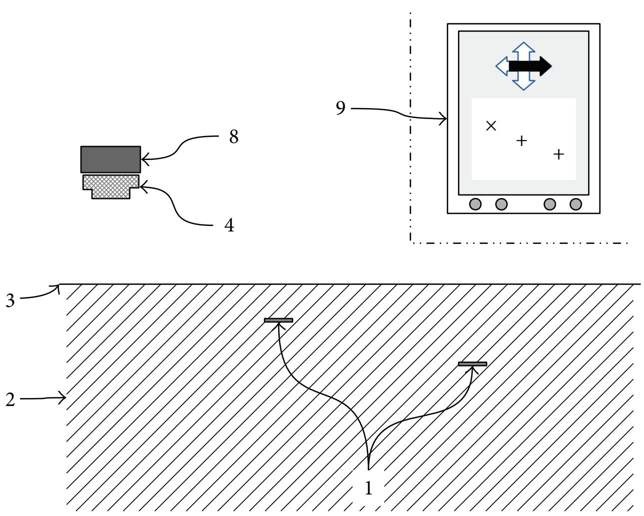


Figure 3: Possible setup for manual data collection, using a portable handheld reader (4) attached to a mobile device (8). RFID tags (1) under the soil (2) surface (3) can be found by a mobile device (8) using a map on its screen (9). The device, such as tablet or smartphone, uses its GPS to store the installation coordinates of each tag and, later, show the sensor localization to the operator.

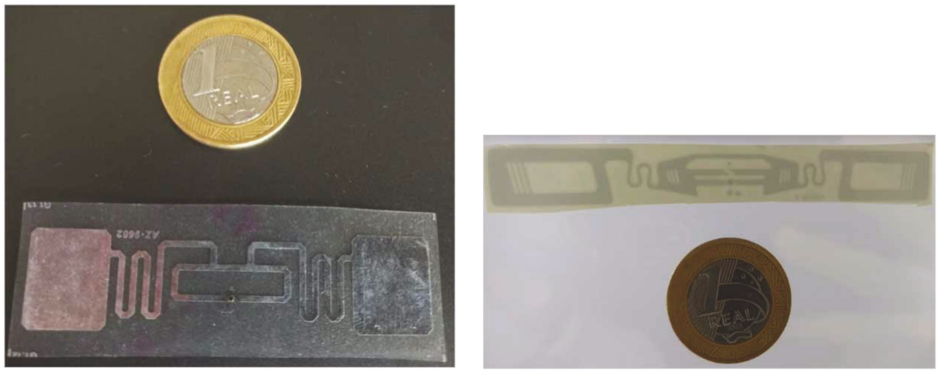
capable of being completely buried on the soil (preferably without wires) to prevent damage due to machines passing by and animals or even people passing by.

Aroca et al. [5] reviewed several related works, discussing some published approaches that involve the use of RFID tags to measure moisture of a wall, of cups, glass bottles, of the soil, among others. In special, Bhattacharyya et al. [6] analyzed the received signal strength indicator (RSSI) to measure the level of liquid on glasses, bottles, and cups. Other authors [7] considered that the presence of water will avoid the RFID tag to work, so a sequence of RFID tags can indicate the level of water on a vase by analyzing which tags are responding and which are not.

The mentioned solutions rely on the analysis of the RSSI during reader-tag communication. Other approaches involve the use of sensor tags, which are RFID tags equipped with specific sensors that can be read and its data reported back to a reader using wireless RFID protocol. Spanish company Farsens [8] sells a batteryless RFID soil moisture sensor, divided in two parts: a sensing element that is buried and an RFID antenna, which is exposed over the soil and can be read in distances of up to 1.5 meters. More recently, the company showed a demonstration of a robot collecting data from their RFID-based soil moisture sensor [9]. Such concept has been primarily presented by Wang et al. [10].

In that way, Bauer-Reich et al. [11] studied the possibility of using UHF RFID technology to communicate with subsurface sensors and concluded that such possibility is viable for sensors at 50 cm depth when soil moisture level is around 15%. Greater moistures lead to significant signal attenuation or complete signal loss. Authors suggest that tags have adequate read ranges for depths of 15 cm.

Between 2016 and 2018, some authors [5, 12, 13] have proposed the usage of standard passive UHF RFID tags as buriable soil moisture sensors, showing the feasibility of such approach; however, none of them present reliable calibration or correlation of real soil moisture content compared to RFID measurements. Berkley and Sivandran [12] even argue that such approach is viable, but the technology is still not mature for a reliable correlation between RFID tag properties and soil moisture.



(a) (b)

Figure 4: (a) Typical UHF RFID tag compared to a Brazilian R$1.00 coin. (b) UHF RFID tag model BJTW01, based on the RFID chip Alien Higgs 3, which is the model used in the experiments presented in this work.

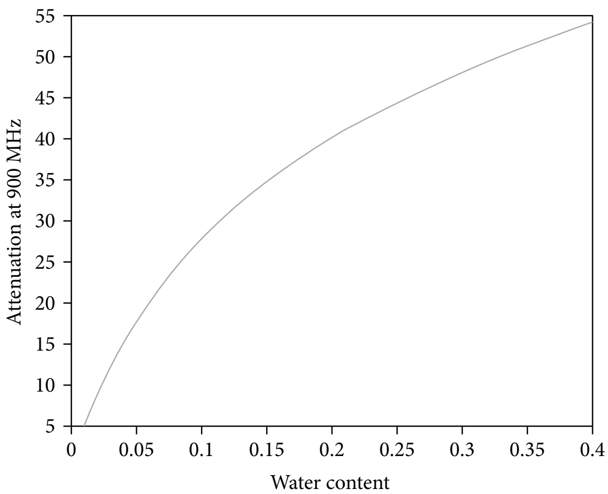


Figure 5: 900 MHz RF signal attenuation under the ground for several water contents on clay soil. Adapted from Miller et al. [16].

The main contribution of this work is the calibration of passive ultrahigh frequency (UHF) radio frequency identification (RFID) technology to provide wireless and batteryless agricultural field sensors that can be buried on the soil and read remotely by a reader device, which can be a handheld reader, an agricultural machine, a central pivot irrigation system, or even a robot. Figure 1 presents an overview of the proposed architecture, where standard passive UHF tags are buried on the soil as soil moisture sensors.

2. Materials and Methods

The main concept of the proposed system is that batteryless and wireless soil sensors can be installed under the soil surface, in one or at several depths, as shown on Figure 2. With such approach, there is no need for maintenance, avoiding the need of battery replacement or possible problems due to parts exposed to the harsh field environment. Data from these sensors can be obtained by several techniques, for instance, manually with a portable RFID reader, automatically with machines, robots, or even irrigation systems.

Figure 3 presents one possible way to read the tags, where an operator, with a portable RFID reader with a display or attached to a smartphone, sees a map of the field and his position. As he walks, he can see if he is over an RFID sensor tag, and when this happens, the reading can be carried out.

Passive tags are the simplest and cheapest types of UHF RFID tags. They operate by harvesting energy from the radio frequency (RF) signal generated by the RFID reader/antenna. These tags typically have memory and other features and communicate with the reader using a technique called backscatter [14, 15], where the tag control chip controls the tag antenna impedance, which reflects the RF signal generated by the reader in different manners. The RFID reader senses the RF signal reflections, caused by the tag's antenna impedance change, and decodes information from a protocol based on this technique. During this communication, the reader is able to measure the received signal strength of the tag, which is available as the received signal strength indicator (RSSI) [14, 15]. Figure 4 shows a typical UHF RFID tag and the one used on this work. One advantage of such tags is that they are produced in high volumes and they have low prices (each tag costs cents of dollars).

2.1. Standard EPC/GEN2 UHF RFID Tags as Soil Moisture Sensors. The idea proposed here, of using standard EPC/GEN2 UHF RFID tags as soil moisture sensors, is described in a related work by Aroca et al. [5], by Berkley and Sivandran [12], and by Pichorim et al. [13]; however, these previous works do not provide calibration or reliable relation between some reference moisture sensor and RFID tag radio frequency (RF) properties. This section provides more details and a proposal for systematic experimental validation of the solution proposed in [5, 12]. The background for using UHF RFID tags as soil moisture sensors is based on the fact that water and moisture attenuate microwave signals. In fact, Miller et al. [16] studied underground microwave communication and presented a relation between water content on the soil and microwave signal attenuation, as shown on Figure 5.

Moreover, and more recently, Mulholland et al. [14] proposed the use of standard RFID tags as people's moisture/sweat sensor, with theoretical and experimental validation

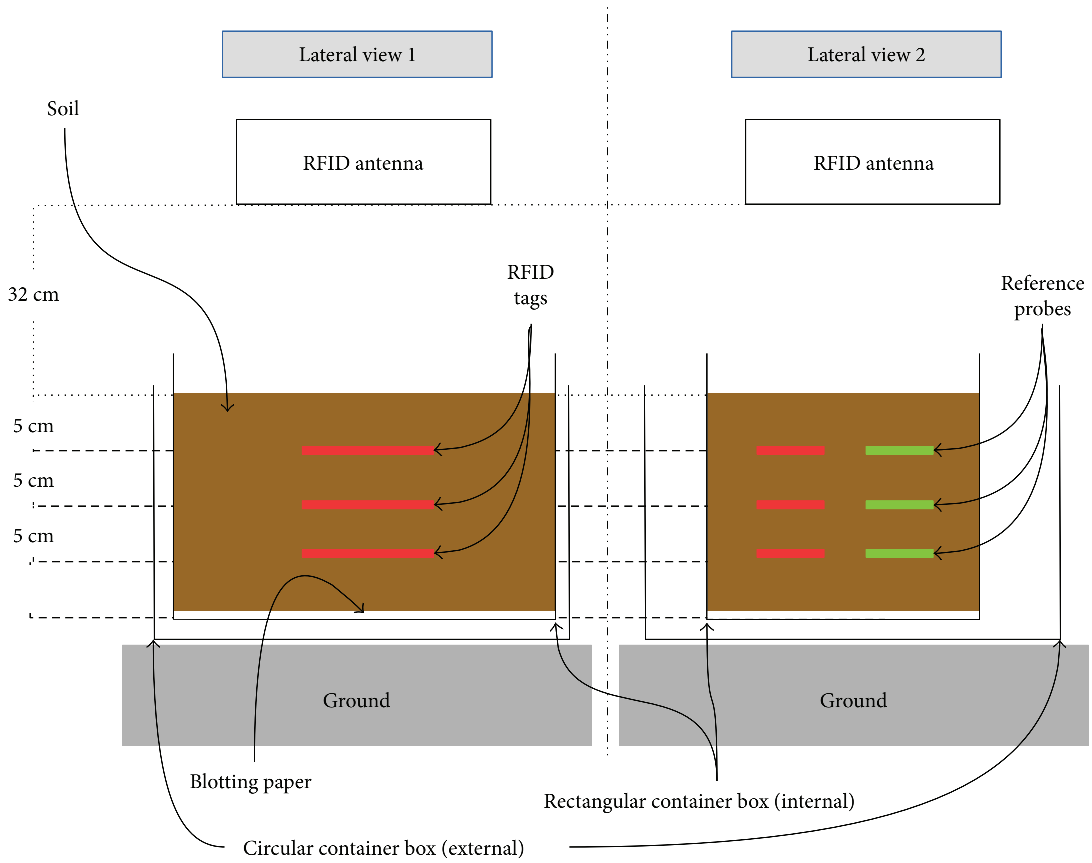


Figure 6: Schematics of the experimental setup, with two lateral views of the same assembly. RFID tags are shown in red, and reference capacitive 5TE soil moisture sensors are shown in green.

Figure 7: Photos of the experimental setup. Internal box with bottom holes; RFID antenna collecting RSSI values from tags on the floor; overall experimental environment; external box filled with water.

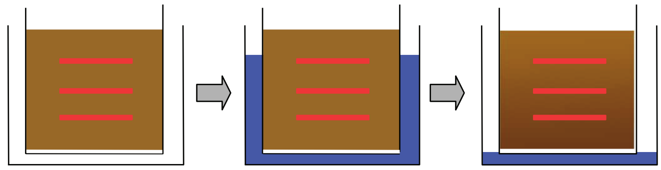


Figure 8: Technique used to wet the soil through the holes on the bottom of the internal container box filled with the oven-dried soil.

Table 1: Structure of collected data and stored in the CSV file. Each value is an average of 3 RFID reader/tag communication property measurement.

Field	Field name	Description
1	TIMESTAMP	Date and time of collected sample (unix timestamp)
2	READ_COUNT	Number of responses from the tag in 15 sec. interval
3	AVG_RSSI_I	Average RSSI value for in-phase channel
4	AVG_RSSI_Q	Average RSSI value for quadrature channel
5	AVG_RSSI	RSSI average value
6	AVG_AGC	Reader automatic gain control
7	AVG_ICOUNT	Average number of readings in the I channel
8	AVG_QCOUNT	Average number of readings in the Q channel
9	AVG_QC	Q channel value
10	AVG_QI	I channel value

of a standard RFID tag for this application, including experiments made on an anechoic chamber. Meng and Li [17] also argue that it is possible to measure moisture using a standard RFID tag with the addition of a substrate, which in the case of this work is the soil. Another work [18] shows the feasibility of using UHF RFID frequencies to measure soil moisture by analyzing radiofrequency properties of RFID antenna and a chipless tag.

Berkley and Sivandran [12] developed a study and conclude that passive RFID tags "*demonstrated a noticeable correlation between the received signal strength and the moisture content of the soil using radio frequencies of* 902–928 MHz," but they did not manage to elaborate a relation or calibration of soil moisture correlated to RSSI or other RF communication property. They conclude that the technique is viable, but further research is needed to establish a known relation. We present results in this direction on this work.

In fact, the calibrations and conclusions of such possibility were obtained experimentally and artificial neural networks (ANNs) were used to learn the soil moisture based on RSSI values and cross-relate them, based on data from a reference capacitive soil moisture sensor.

It is important to note that, although RSSI and soil moisture could be directly related in theory, this was not possible due to several RFID techniques to increase the communication reliability between reader and tag. In fact, the conducted experiments have shown that the RFID reader (AMS RADON based on the AS3993 chipset) uses several techniques to improve performance. In special, we observed that the automatic gain control (AGC) and the automatic switching of real/imaginary (I/Q) channels (90° phased out) cause unexpected RSSI readings, which make it difficult to infer soil moisture directly from the raw RSSI readings.

The proposed calibration, which has shown good results to establish a RSSI to soil moisture relation, consists in the usage of artificial neural networks (ANNs) that are trained and, thus, learn the soil volumetric water content based on the RFID communication properties at each instant. After being trained, the neural networks are used as mathematical functions that map RF parameters obtained by the reader to the volumetric water content (VWC) in m^3/m^3. In this way, the ANNs implicitly also store a calibration for the RFID tags used as soil moisture sensors.

Another part of this work is the development and usage of a mobile robot to autonomously drive until each sensor tag and obtain the measurements automatically. The robot construction is proposed and discussed in another work [19] and now is integrated and used in this work, including the use of a uBlox NEO-M8P Real-Time Kinematics (RTK) Global Positioning System (GPS) receiver, that can reach positioning precision of a few centimeters thanks to a fixed GPS station for GPS correction.

3. Results and Discussion

In order to study the correlation between RFID tag communication properties and soil moisture and perform the calibration, the following experiment was prepared and conducted: a rectangular container box of 60 liters capacity was assembled inside a circular container box of 80 liters capacity.

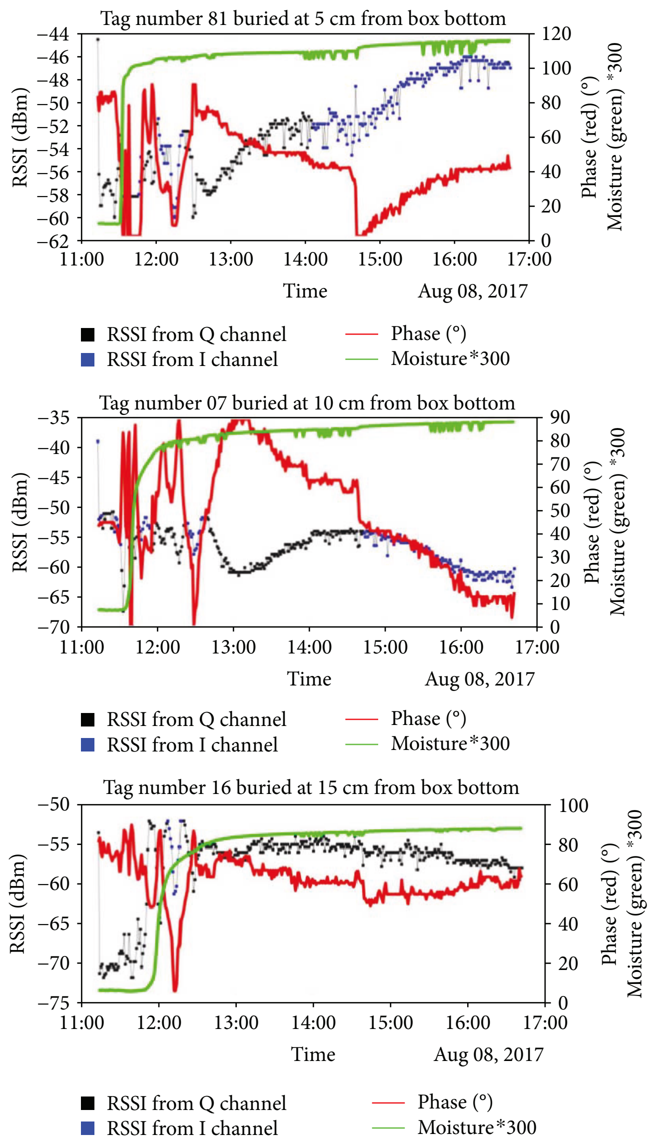


Figure 9: Normalized RSSI data from tag number 81, number 07, and number 16 which was buried at 5, 10, and 15 cm from box bottom. Scatter blue and black represent RSSI signal and from which channel it was chosen. Red line represents the signal phase estimate, using I and Q channel data. Green line is the moisture measure from reference sensor multiplied by 300 so it can fit the scale.

Figure 6 shows a schematic diagram of the experimental setup, where the mentioned container boxes are shown in two different lateral views (width and length).

The internal box was filled with an Oxisoil soil (Quartzipsamments, 86% sand content) up to 20 cm height. For the experiment, 3 RFID tags were installed in parallel to 3 reference conductive soil moisture sensors, as seen in the diagram of Figure 6. The internal box was prepared with 190 holes of 3 mm diameter equally spaced on its bottom at each 20 mm. Before adding the soil, the bottom of the internal box was covered with blotting paper over the holes, to avoid the soil from escaping via the holes. The RFID antenna is assembled 53 cm from the ground and 32 cm from the soil surface. This distance was considered because it gives about 30 to 50 cm distance from antenna to tags, which are common root depths in many crop cultures.

The tags and reference sensors were installed while the soil was being added to the box in three different depths. After the experimental setup was ready, with all the soil, RSSI and other tag parameters/volumetric water content (VWC) were measured during 20 minutes. This is considered the dry soil reference, as the soil was previously oven dried at 105 degrees Celcius for 24 hours. Figure 7 shows some photos of the experimental setup.

The soil sample was initially wet by adding water on the external container box and refilling it constantly until it reached the soil surface (on the internal box) by capillary forces and was left overnight to reach equilibrium. Note that the soil container has holes on its bottom to allow water to enter from the bottom only. Then, water was added to the external container box up to 20 cm height and left for some hour to force full saturation, and after that, the excess of

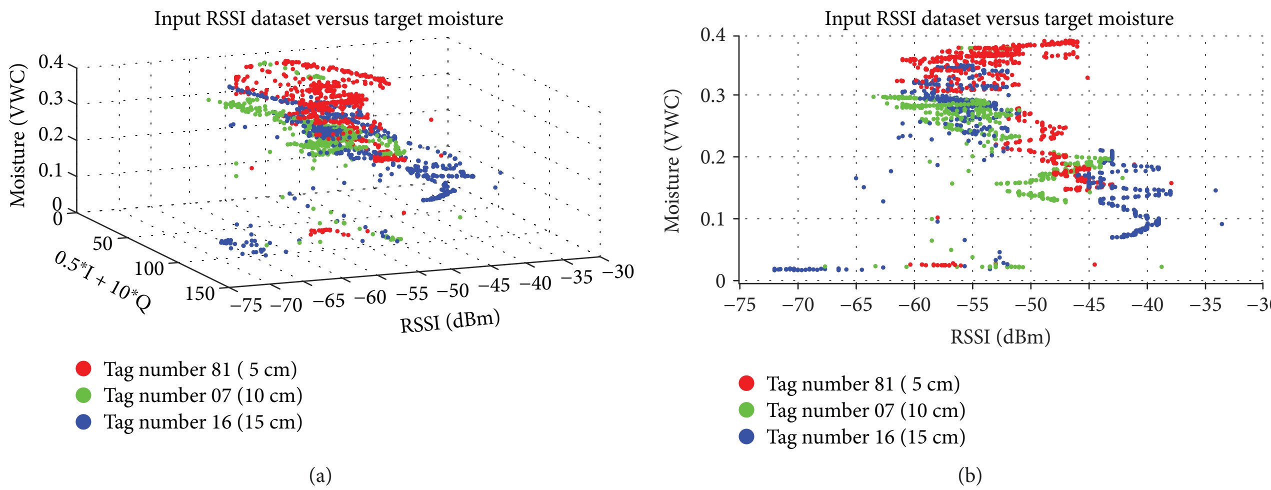


Figure 10: All dataset collected. Red dots are from tag number 81, green dots are from tag number 07, and blue dots are from tag number 16. (a) Reference moisture plotted against RSSI signal and I/Q channel information. (b) Projection of data on reference moisture plotted against RSSI.

Table 2: Training, validation, and test results for the artificial neural network used to correlate soil volumetric water content with RFID tag signal properties while the soil moisture was rising. MSE: mean square error.

RFID tag depth	ANN training (85% samples per depth)		ANN test (15% samples per depth)	
Measure	MSE	R^2	MSE	R^2
5 cm	$6.2e-04$	0.97	$2.1e-03$	0.89
10 cm	$3.84e-05$	0.99	$2.9e-03$	0.78
15 cm	$1.52e-04$	0.99	$1.9e-03$	0.91

water on the external contained was removed by siphoning. Details about the soil wetting procedure are presented in Figure 8.

As for the RFID reader, the AS3993 Demo Kit Radon reader from AMS was used attached to a 7 dBi RFID patch antenna from Poynting (model PATCH-A0025) for 860 to 960 MHz frequencies with circular polarization. A program was developed to continuously collect and store the several RFID/RF data, with a timestamp for later comparison with the reference sensors. For the reference sensors, three Decagon 5TE capacitive soil moisture sensors with SmarTrac data logger were used, collecting data at each minute. The RFID tags used were the BJTW01, based on the chip Alien Higgs 3. It is important to note that these tags were encapsulated in plastic bags to avoid water/moisture to directly interact with the tag antenna/circuit.

Collected data were stored in a comma-separated value (CSV) file, and the experiment was conducted over a period of one month. Table 1 shows the structure of the collected data, which is available under request. Data provided by the Decagon SmarTrac data logger is not presented as we used the standard spreadsheet generated by the Decagon data logger.

An exploratory data analysis was carried out to assess which factors may be affecting the RSSI signal. The data were divided by the depths that the tags were buried: tag number 81 was buried from 5 cm of the internal box; tag number 07 was buried from 10 cm of the internal box, and tag number 16 was buried from 15 cm of the internal box and was divided by event. On the first day, the dry soil got wet until it became a water-soil solution (no air), and this part of data was called moisture rising. On the other part, the water of the outer box was completely removed, and for a couple of hours, the water that fell down was also dried out from the bottom. After that, the soil had approximately 1 month to dry out, and this part was called moisture decreasing.

As mentioned before, the AS3993 reader chooses I or Q channel (which are 90° phased out) to log as RSSI signal and also automatically adjust gain; the RSSI signals do not have a smooth curve as shown in Figure 7 (theoretical model). Thus, a gain compensation has to be done for the signals collected. Moreover, as there is the channel-swapping events, it is important to register from which channel the information is coming from and, as both channel information is available, it is possible to have a rough estimate of the signal phase. Furthermore, there are times that the tag becomes unresponsive, meaning that it does not have the minimum signal strength to be powered and respond to the reader inquiry.

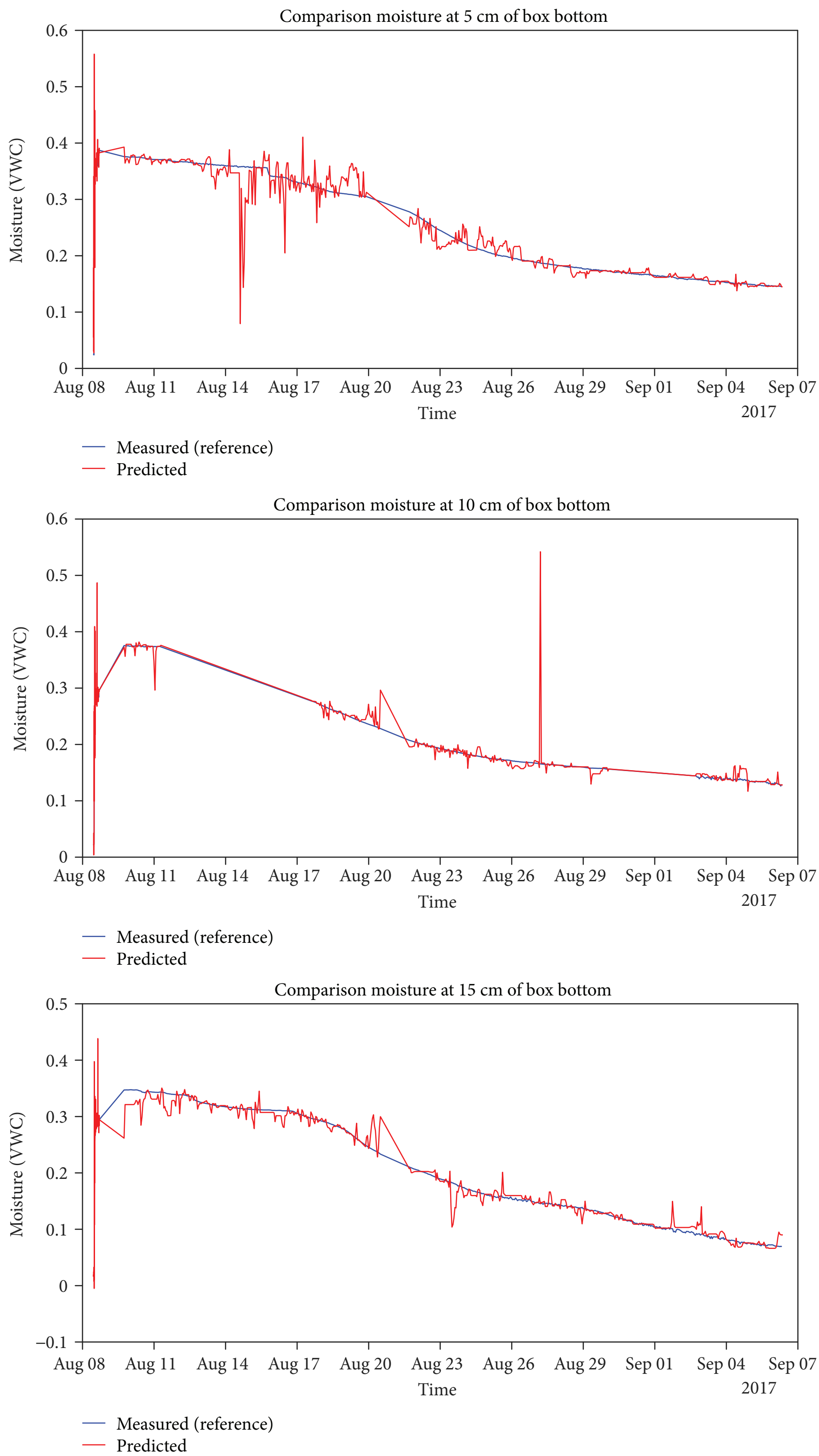


Figure 11: Artificial neural network soil moisture (volumetric water content, in m^3/m^3) was predicted based only on the RFID tag signal analysis.

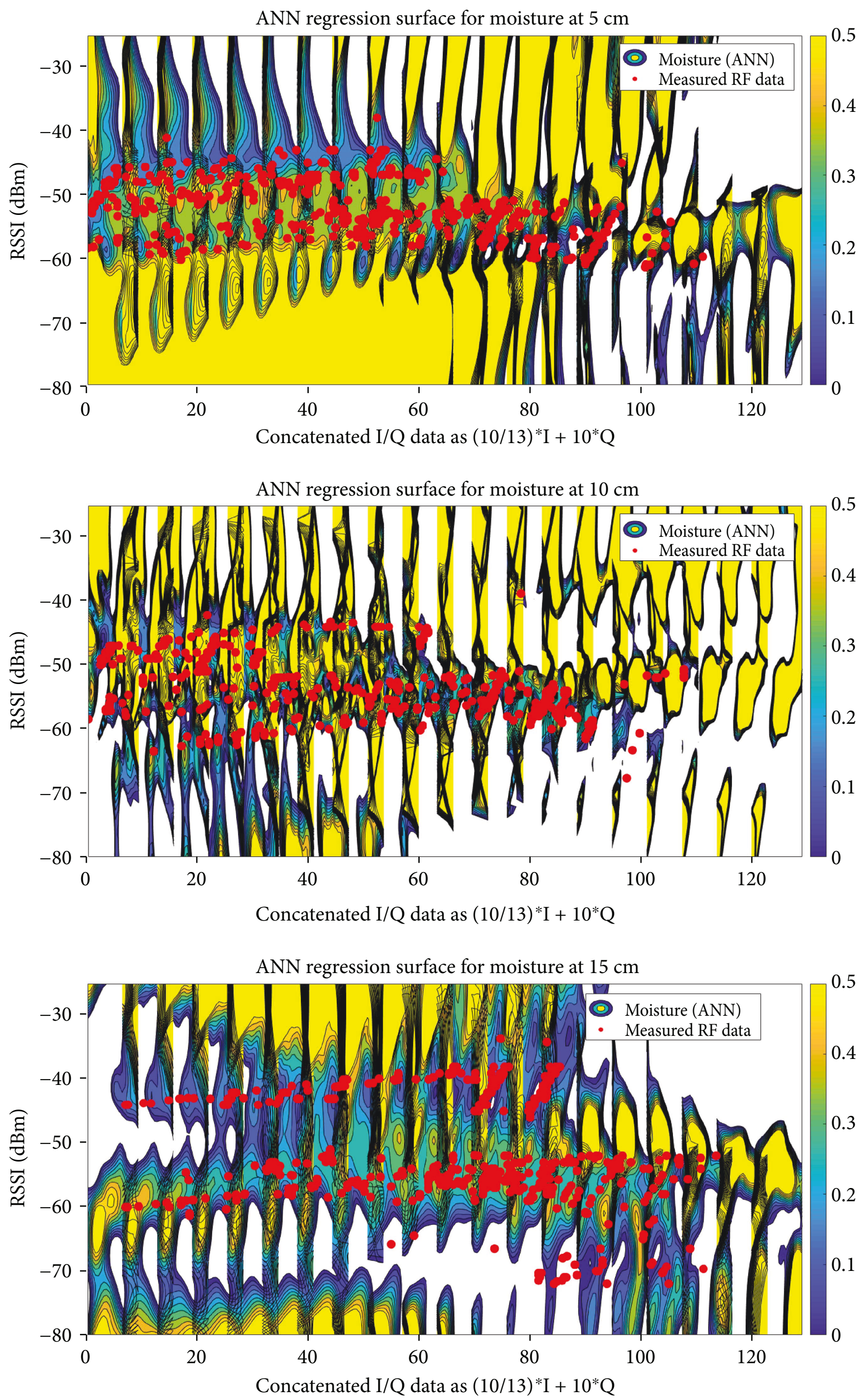


Figure 12: Artificial neural network regression contour map for soil moisture (volumetric water content, in m^3/m^3). Red dots are the collected points.

Figure 9 depicts the evolution over time for the first hours of the wetting and moisture rising experiment phase for the 3 depths based on the data collected with gain adjusted. In all the plots, the Moisture*300 line presents the (reference) capacitive sensor readings, which is shown multiplied by 300 simply for better graphic representation. The highest VWC observed was 0.4 m^3/m^3.

Figure 9 shows the tag at higher depth (5 cm from the bottom), the one with greater distance from the reading antenna, and, as expected, the first to be wet. Its RSSI measurements follow not only moisture but also the phase signal. For the tag at 10 cm depth, a trend is noticeable, while Q channel increases, I channel reduces amplitude (90° delayed). For the tag with 5 cm of soil over it, a more

Figure 13: Mobile robot used to read underground batteryless and wireless soil moisture sensors of this work.

stable trend can be noted. In the analysis performed, several regression approaches were tried to correlate RSSI, phase, and other RF communication data with the soil moisture read from the 5TE sensor; however, none of them presented a reliable correlation (all tests presented R^2 less than 0.4). Figure 10 shows the complete dataset analyzed, with the I/Q channel information was collapsed as ($0.5^*I + 10^*Q$) to ease data visualization.

When analyzing the whole dataset, it is possible to observe a complex scenario for calibration. There is no apparent trend on display, and the same RSSI value has more than one correlation with moisture content. Also, in this line of thought, it is also clear that same RSSI value has different moisture for each tag (depth) they encounter. Thus, a nonlinear regression has to be made to overcome the aforementioned difficulties.

An artificial neural network (ANN) was trained, tested, and validated with the experimental data. The theoretical background of how an ANN works is not on the scope of this work, so for further information about this subject, we recommend the textbook by Russel and Norvig [20]. The ANN was implemented in Matlab, and its architecture consists of an ANN with intermediate layer having 60 neurons with hyperbolic tangent sigmoid transfer function and the exit layer having 1 neuron with linear function.

All the time data was used, from moisture rising and moisture decreasing phases. A point of observation has to be made, as the rising occurred faster than the decreasing phase, the first was averaged at every 5 minutes, and the second at every hour.

Experimental data was divided into 3 data sets, one for each tag, and the choice for each ANN can be easily done via a database with the tags and its depth. The input signals were the RSSI value, the raw I and raw Q channel data. The training method was Bayesian regularization, as suggested by Matlab for difficult and noisy datasets. Table 2 summarizes the ANN information and results. For each ANN, a part of the samples was used for training and another part for testing the ANN.

Figure 11 presents plots of volumetric water content on the soil predicted by each ANN, one for each depth, based only on RFID tag and reader communication properties. The results are closely related to the measurements of the reference capacitive sensors. These results show that the ANNs have shown good convergence.

As explained, three ANNs were designed and trained for each tag depth, and both for moisture increasing and decreasing. Figure 12 shows the regression surface of these three ANN. From the regression surfaces contour maps, it is possible to see that the proposed ANN solution were able to encapsulate all data points; by analyzing how the regression was done by the ANN, it can be concluded that there is no simple model that could fit the system as complex as it was used.

Overall, the ANN approach has shown to be adequate and reliable to estimate soil moisture for the Oxisoil soil. Also, a trained ANN for a single point, as it should be when it is deployed, is considerably fast considering modern embedded computers; thus, this calibration solution is feasible to be implemented on a robot or other device/equipment. Future works could study the variations for other soils; however, the presented results answers the gaps left on other related works [5, 12].

Finally, on a longer experiment, nine passive tags were prepared and installed on the soil for long-term tests, at 3 different depths (5 cm, 20 cm, and 40 cm). These tags were installed on the year 2014 and are still operational on March 2018, which shows that even these nine low-cost tags are robust enough to endure several years of underground operation. All of them are still responding, and their RSSI can be measured to estimate soil moisture.

The proposed method can provide data to manual or automated systems. Figure 13 shows a photo of an example application, where a mobile robot was capable of driving until each sensor position and collecting underground sensor data. The robot operation is not the focus of this work, but using a GPS RTK, it can be able to position itself with a few centimeter precision, which is important

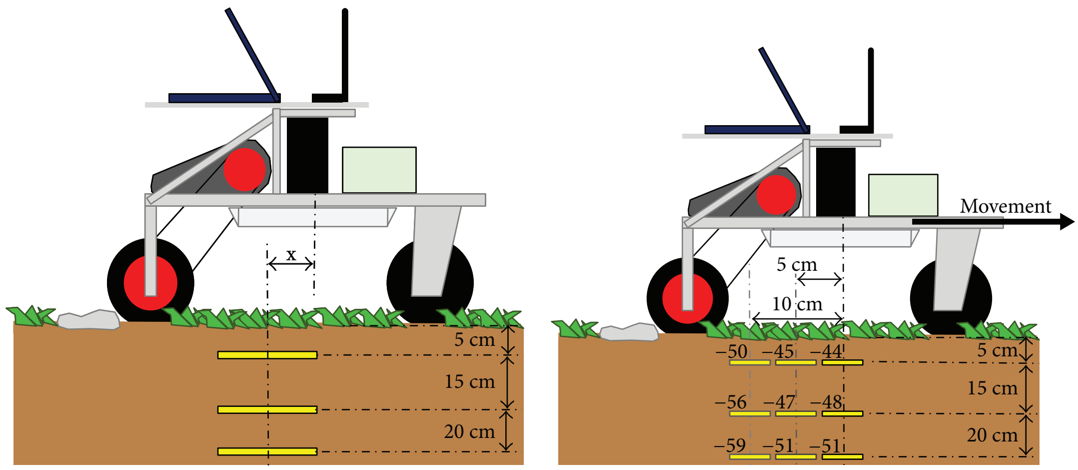


Figure 14: Examples of mobile robot collecting data from the sensors at different positions, which affect the RSSI readings, as shown in (b).

for this application, as different antenna position will result in different RSSI measurements. As shown in Figure 14, especially for the RSSI-based soil moisture measurement, the antenna position is important to guarantee reliable data reading.

4. Conclusions

Water is a vital resource for the society, especially for crop production. For the agricultural activities, especially plant growing, water is a key resource that is mostly needed. However, each time more, a rational and finely controlled water usage is desired. For that end, several types of soil moisture sensors are available, but they typically need cables and batteries.

This article describes the calibration of RFID technology using passive UHF tags applied to measure soil moisture without battery and wirelessly. The presented approach relies in analyzing the communication properties between RFID reader and tags. Experimental measurements collected RFID tag communication and related it to reference capacitive soil moisture sensors. Then, neural networks were used to establish a correlation between volumetric water content on the soil to RFID tags RSSI, phase, and other properties. In general, the designed artificial neural networks, after training, were able to compute (predict) soil moisture with $R^2 > 0.9$ in most cases.

A mobile robot was also designed and built, which is capable of navigating until each sensor to collect sensor data automatically. This robot was used as a proof of concept, because, as discussed, other devices, such as a center pivot system irrigation system, can be equipped with RFID readers to measure soil moisture during daily operations.

For future works, different soils can be evaluated with the RFID tag as moisture sensors. Moreover, other inputs to the ANN can be tested, such as soil model, to encapsulate 3 ANNs in one. Further, other ANN architectures could also be evaluated.

Data Availability

All the collected data, source codes, and further information are freely available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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